The design of stellar interferometers I

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Outline

- What's the science?
- Fundamental limits—the photon limited signal to noise ratio
- Practical limits I: atmospheric effects and mitigation techniques
- Practical limits II: instrumental and optical limitations
- Summary

The science drivers

- Wavelength coverage
- Bandwidth $\Delta\lambda$
- Resolution: λ_0/b
  - Coverage of the (u, v) plane
- What imaging capabilities do you want?
- Practical limitations: budget & staffing

Fringe detection I

- The *complex coherence* is the technical term for the *theoretical* fringe visibility and is usually written as

$$\gamma = |\gamma| \exp\{i\phi\}$$

- We want to measure $|\gamma|$ and ϕ separ-ately. How do we do this in practice?

Fringe detection II

- Formally,

$$|\gamma|^2 = \mathrm{Re}^2\{\gamma\} + \mathrm{Im}^2\{\gamma\}$$

$$\tan\phi = \mathrm{Im}\{\gamma\} / \mathrm{Re}\{\gamma\}$$

- For smallish bandwidths,

$$\mathrm{Im}\{\gamma(x)\} = \mathrm{Re}\{\gamma(x + \lambda/4)\}$$

(strictly, we want to do a Hilbert transform, but that's another story).

Implications

- When the visibility is small (for example, $b >> \lambda/d$), the "correlation" V^2 will be *really*, *really* small.
- This limits the *dynamic range* of the interferometer; i.e., the ability to detect low surface brightness features.

The bottom line: the SNR

- As a consequence, we normally estimate the “correlation” or square of the complex coherence function $|\gamma|^2$.
- The *measured* visibility is V^2 and the SNR is

$$V^2 N \Delta t \left[\frac{T / \Delta t}{2(1 + 2N \Delta t V^2)} \right]^{1/2}$$

where N is the photon flux thru one aperture, Δt the sample time and T the total integration time.

Practical difficulties

- The *observed* "correlation" or square of the visibility is always *less* than $|\gamma|^2$:

$$V^2 = \eta^2|\gamma|^2$$

where $\eta < 1$ is a time-varying loss factor.

- *The reliable estimation of the visibility loss factor η is the biggest problem remaining in optical/IR interferometry*.

The constraints imposed by the Earth's atmosphere

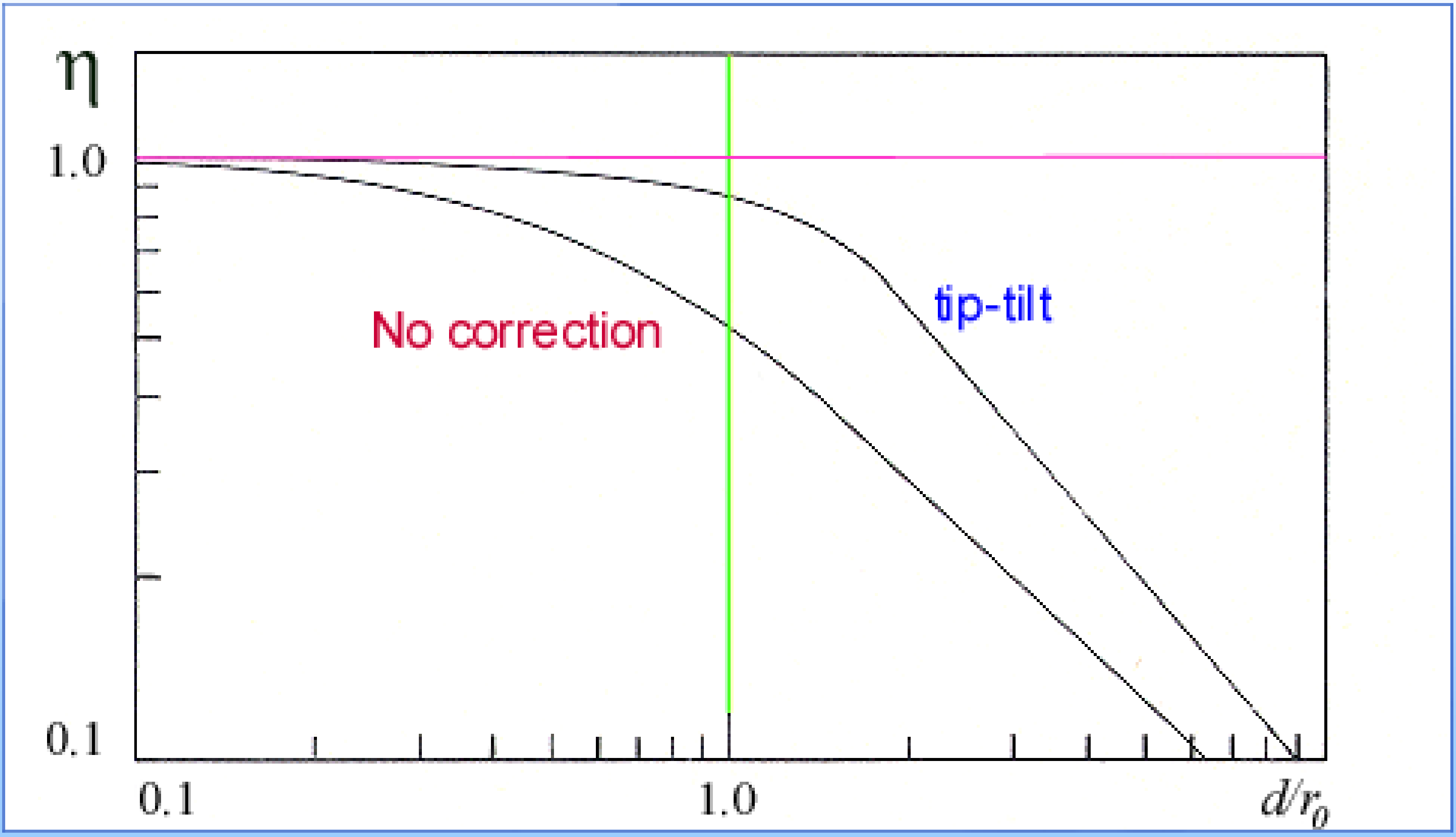
Aperture size

- Visibility loss depends on d/r_0.
- Since r_0 varies as $\lambda^{6/5}$, the optimal aperture size will depend on the wavelength.
- Larger apertures can be used in the IR than in the visible part of the spectrum.

Adaptive optics

- Adaptive optics is essential to reduce the effects of atmospheric turbulence and instrumental effects (i.e., image motion due to gear errors, etc.).
- All interferometers use at least “tip-tilt” wavefront correction.
- Recall: $\eta > 0.9$ when $\alpha < 0.3\lambda/d$

Tip-tilt correction



Tip-tilt servo performance I

- In practice, *noise* restricts the useful bandwidth for a tip-tilt servo.
- Finite bandwidth means less than perfect correction (high frequency tip-tilt components remain).
- With a Taylor wind speed v_T, the coherence loss is ~10% when the cut-off frequency f_0 is $\sim v_T/\pi d \approx (r_0/d)/(10t_0)$

Tip-tilt servo performance II

- Typical bandwidths are in the range 20 ~ 100 Hz.
- Performance also depends on the detector and amount of light. The effect of noise is to add fluctuations: $<\Delta\theta^2> = 4\Delta f_B\ \theta_0^2/N$ where N is the photon flux, θ_0 is the effective image size, and $\Delta f_B \approx f_0$ is the noise bandwidth of the servo.

Spatial filtering

- Passing light through a spatial filter (pinhole or single-mode fiber) removes aberrations. The factor $\eta \approx 1$.
- Tip-tilt is still needed to guide light into filter/fiber.
- Examples: the FLUOR detector (used at IOTA), the pinhole filter at COAST...

Optical path length I

- To observe an interference signal, the OPL difference must be less than the *coherence length* $\Lambda_{coh} = \lambda_0^2/\Delta\lambda$.
- The large amplitude, low frequency atmospheric fluctuations basically introduce a slowly fluctuating OPL difference. Its importance depends on the bandwidth.

Optical path length II

- Small amplitude, high frequency fluctuations cause phase jitter during individual sample times Δt.
- Ideally, $\Delta t << t_0$, the atmospheric coherence time.
- From the Taylor hypothesis, t_0 is related to r_0 by $t_0 = 0.314 r_0 / v_T$.

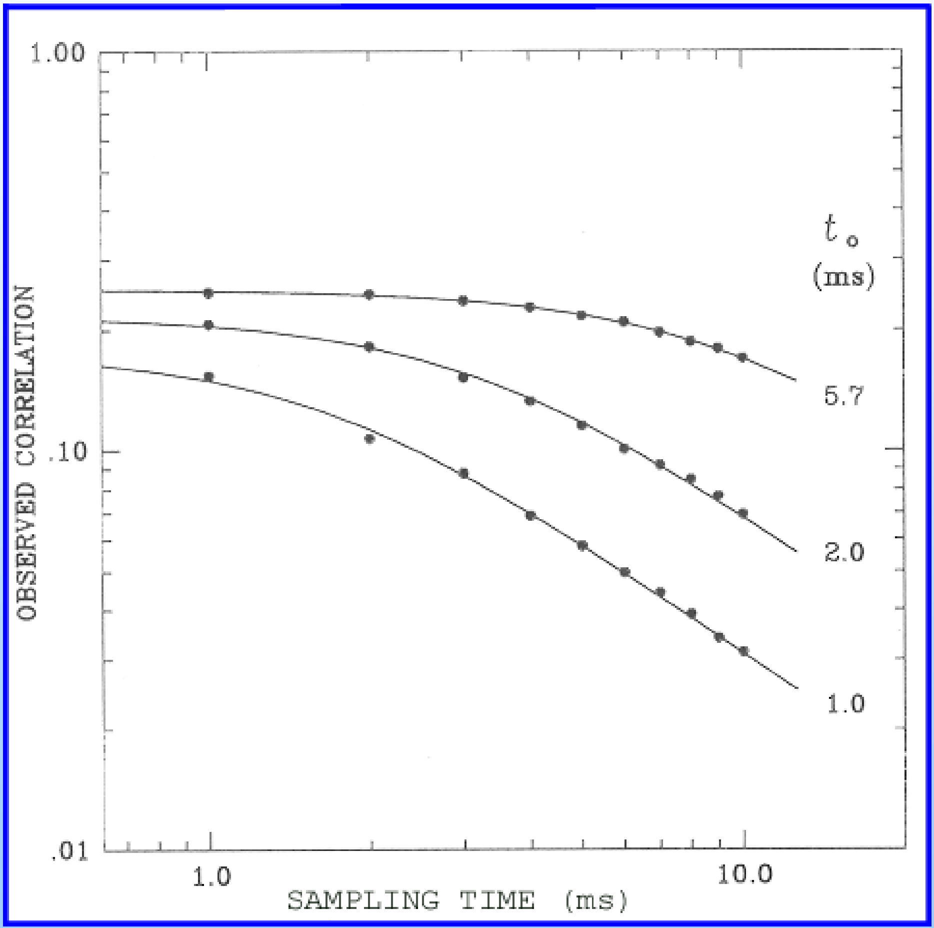
Effect of sampling time

- Buscher defined the atmospheric coherence time t_0 through

$$D_\phi(t) = <|\phi(t') - \phi(t'+t)|^2> = (t/t_0)^{5/3}$$

- If the sampling time Δt is greater than t_0 the phase fluctuations reduce the visibility/correlation.
- However, we can use Buscher's results to extrapolate to zero sample time:

Correlation vs. sample time



Solid lines are fits to the measured correlation data (adapted from Davis & Tango,1996).

Caveats

- The 2, 3,... ms sample times are synthesized by binning 1 ms samples.
- The data points are therefore not independent.
- At low correlation ($C < 0.2$, approx.) or when $t_0 \sim 1$ ms or less, the method tends not to work (better algorithms?).

Limitations to performance

- The coherence time t_0 is 1~5 ms (visible).
- As the OPL rate increases, mechanical vibration becomes an important consideration.
- One must also limit vibrational noise from air conditioning, etc.

Controlling the OPL noise

- Coarse control is provided using motorized carriages.
- Fine control is often done with PZTs
- Voice coil actuators are also in common use.
- Frequently several levels of isolation are used.

Dispersion

- The external OPL difference is *in vacuo* (flat Earth approximation).
- If path compensation is in air, differen-tial dispersion becomes an issue.
  - *Dispersion compensation can be used (variable amounts of suitable glasses)*
  - *Alternatively, the compensator system can be evacuated.*

Metrology

- The OPL difference must be monitored with an accuracy of $<<\lambda_0$.
- Laser metrology is essential.
- The amount of metrology needed depends on the design. *Astrometric* interferometry is especially demanding and requires additional metrology.

Calibration

- In theory, one *calibrates* measurements by observing calibrators with known visibility and the science target.
- In practice, calibrators must be close to the science target in order to get an accurate estimate of η.

Instrumental factors

Optics

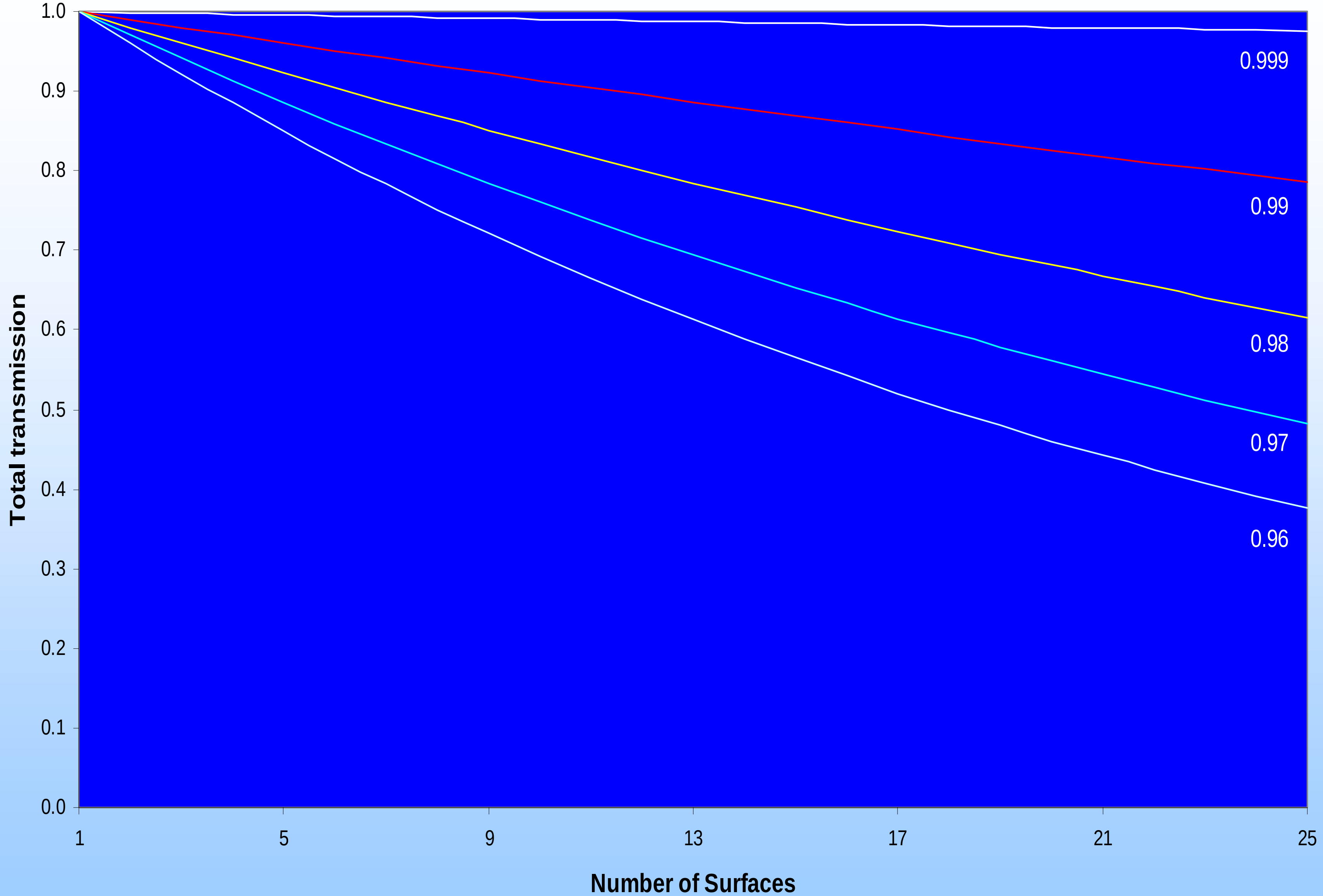
- Visibility loss is proportional to the mean squared phase variation:
  $$|\eta|^2 = 1 - \Delta^2\Phi = 1 - (2\pi/M)^2$$
  where the *total* optical *figure* is λ/M.
- If the average figure per surface is λ/m, then M will be approximately
  $$m/N^{1/2}$$
  where N is the number of surfaces (often classified information!).

Optical alignment

- The alignment of the optics is critical, particularly for non-planar elements.
- Off-axis aberrations
- Shear (incorrect superposition of pupils) is unique to interferometers.
- “Artificial stars”—often used in auto-collimation mode—are essential.

Optical Thin Film Coatings

- If r is the reflectivity of a single surface, the overall transmission is proportional to r^N, where N is the number of surfaces.
- OTF coatings are routinely used to minimize losses, but beware!
- Performance in the field is often much below manufacturers' specs.

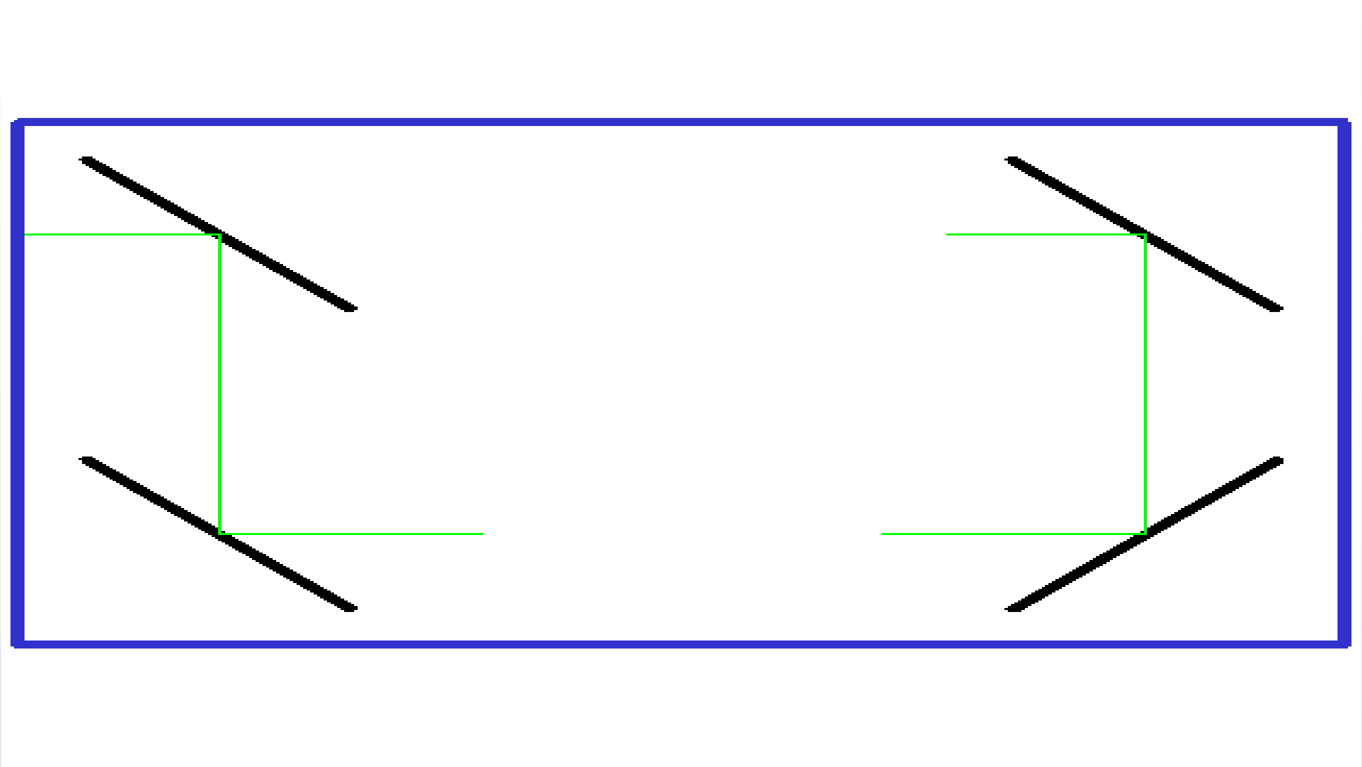


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Total transmission
0.999
0.99
0.98
0.97
0.96
1
5
9
13
17
21
25
Number of Surfaces

Polarization

- The visibility will be reduced by the factor $\eta_P = (I_p \cos\Delta\phi + I_s)/(I_p + I_s)$ where $\Delta\phi$ is the phase difference between s & p polarizations.
- Geometry and OTF coatings can both introduce phase shifts.
- Solution: separate the polarizations!

Geometric phase: example



- Note: this is also known as the Panchar-atnam or Berry phase.

Diffraction

- Interferometers are unique. They have long internal paths & relatively small apertures and near-field diffraction effects cannot be neglected.
- Unequal *internal* paths lead to visibility losses.
- Diffraction effects are particularly serious for longer wavelengths.

Control & data acquisition

- Modern control systems (servos) use computers to “close the loop.”
  - Intrinsically more flexible than traditional “hard-wired” systems, but...
  - They are not perfect! *Latency* is the biggest problem.
- Consider using real-time operating systems (POSIX standard, RT-Linux).

Embedded processing

- A common solution is to use "embedded processing."
- Data flows between processors are critical. TCP/IP is potentially dodgy. Examples of critical systems:
  - Metrology, the OPL controller, and fringe detection/tracking system.
  - Telescope control & tip-tilt system.

Data acquisition

- Details will depend on the way the fringe visibility is measured.
- System must provide feedback to the observer about the quality of the data.
- A standard procedure for recording and archiving data must be adopted.

Summary

- Operating wavelength, bandwidth, site location
- Match apertures to r_0
- Tip/tilt adaptive optics
- Optical path length compensation & phase stability
- Dispersion: vacuum or air

Summary, cont'd

- Metrology
- Optics: quality & quantity
- OTF coatings
- Polarization—dynamic & geometrical phase shifts
- Diffraction
- Control & data acquisition systems